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Saccadic target selection as a function of time

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Abstract—Recent evidence indicates that stimulus-driven and goal-directed control of visual selection operate independently and in different time windows (van Zoest *et al*., 2004). The present study further investigates how eye movements are affected by stimulus-driven and goal-directed control. Observers were presented with search displays consisting of one target, multiple non-targets and one distractor element. The task of observers was to make a fast eye movement to a target immediately following the offset of a central fixation point, an event that either co-occurred with or soon followed the presentation of the search display. Distractor saliency and target-distractor similarity were independently manipulated. The results demonstrated that the effect of distractor saliency was transient and only present for the fastest eye movements, whereas the effect of target-distractor similarity was sustained and present in all but the fastest eye movements. The results support an independent timing account of visual selection.

Keywords: Saccadic visual selection; stimulus-driven control; goal-driven control; eye movements; bottom-up and top-down; attention.

INTRODUCTION

It is generally believed that saccadic target selection can be either involuntarily controlled by stimulus properties in the visual field or voluntarily controlled by the goals and intentions of the observer. These two manners of control are often referred to as stimulus-driven and goal-driven control of visual selection, respectively. While it is generally accepted that both influences play an important role in controlling saccadic target selection, models of selection typically tend to stress the importance of one control mechanism.

Several authors suggest that saccadic target selection is predominantly controlled by stimulus properties in the visual field (Engel, 1977; Godijn and Theeuwes, 2002;

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Kramer *et al.,* 1999; Theeuwes and Godijn, 2001). Accordingly, it is assumed that saccades are directed to the most salient object in a visual scene, regardless of the goals and intentions of the observer. For example, Theeuwes *et al.* (1999) showed that when participants are required to make a voluntary, goal-directed saccade to a color singleton target, the planning and execution of the goal-directed saccade towards the singleton target was disrupted by the appearance of a new element. Theeuwes *et al.* concluded that visual selection initially is determined by the stimulus properties in the visual field. Goal-driven control may play a role, but only after stimulus-driven selection has taken place. According to a bottom-up model of saccadic selection (Theeuwes *et al*., 1998, 1999), goal-driven selection occurs after, and is contingent on stimulus-driven selection.

Other research, however, suggests that target selection may be predominantly controlled by the goals and intentions of the observer (e.g. Findlay, 1997; Williams and Reingold, 2001). Accordingly, when certain characteristics of the target are specified in advanced, the searcher tends to fixate objects possessing those characteristics over other objects (e.g. Williams, 1967). For example, Findlay (1997) showed that saccades are more likely to be directed to a non-target sharing a feature with the target as compared to other non-targets sharing no features with the target. When participants were asked to search for a conjunction of color and shape, the percentage of erroneous saccades that landed on a stimulus that possessed a target feature was higher than expected by chance (Findlay, 1997; Findlay *et al.*, 2001). Thus, initial selection is assumed to be determined by the goals and intentions of an observer. According to a top-down model of selection (e.g. Folk *et al.*, 1992, 1994), stimulus-driven selection may take place, but only after and contingent upon goal-directed selection. That is, it is assumed that a salient stimulus will only attract the eyes if it shares features with a target an observer is searching for.

In contrast to the idea that visual selection is predominantly controlled in a stimulus-driven or goal-driven manner, other accounts of visual selection do not stress the importance of one of the mechanisms, but have argued that visual selection is determined by both stimulus-driven and goal-driven influences (Treisman and Sato, 1990; van Zoest and Donk, 2004; Wolfe, 1994; Wolfe *et al.*, 1989). For example, according to Guided Search (Wolfe, 1994; Wolfe *et al*., 1989) information from the visual field is broken down and represented in several feature maps each signaling the presence of simple features such as orientation and color. The separate feature maps are subsequently combined in one general activation map. Attention is deployed to the most active location in the activation map. It is argued that information from each feature dimension involves both stimulus-driven and goal-directed activations (Wolfe, 1994; Wolfe *et al*., 1989). Stimulus-driven activation is a measure of how unusual an item is in its present context. The strength of stimulus-driven activation for one location is based on the differences between it and items at neighboring loci (Wolfe, 1994). In addition to these stimulus-driven activations, goal-driven activations also modulate the different feature maps. Knowledge of the task requirements may influence the relative contributions of different feature maps

in that different features may receive different weightings. As such, stimulus-driven and goal-driven activations build up independently in each of the various feature maps and are subsequently combined in an overall activation map. In turn, the effects of stimulus-driven and goal-driven control summate to jointly influence the allocation of attention.

Recently, van Zoest *et al.* (2004) elaborated on the idea that both stimulus-driven and goal-directed activation ultimately come together in one common general activation map. However, different from the idea that at any given moment both influences summate to determine selection, van Zoest *et al.* proposed that stimulus-driven and goal-driven control *independently* contribute at different points in time. Accordingly, our work has shown that saccadic visual selection is initially completely stimulus-driven, whereas goal-driven control dominates visual selection later in time (see also, Connor *et al.*, 2004). Van Zoest *et al.* (2004) required participants to make a speeded saccade towards a predefined target presented concurrently with multiple non-targets and one distractor. The distractor was more salient, equally salient or less salient than the target. The results showed that the effect of salience critically depended on the time at which a response was elicited. Saliency only affected search when eye movements were elicited early in time. When an eye movement was elicited later in time no effect of saliency was observed. Instead, later in time, eye movements appeared to be increasingly more goal-driven. According to an independent timing account of visual selection (van Zoest *et al.*, 2004), visual selection is the outcome of two independent processes, one stimulus-driven and the other goal-driven, operating in different time windows.

However, in our previous experiments, variables affecting goal-driven control were not manipulated; only variables affecting stimulus-driven control were manipulated. The present study aims to independently manipulate variables affecting goal-driven control as well as variables affecting stimulus-driven control.

In the current experiment, observers were instructed to make an eye movement to the target when the fixation point was extinguished. The fixation point either offset concurrently with the presentation of the search display, or at a variable interval after stimulus display. Previous research has shown that if the fixation point disappears simultaneously with the search display, saccades are facilitated (e.g. Kingstone and Klein, 1993; Reuter-Lorenz *et al.*, 1991). In contrast, forcing observers to make an eye movement some time after the presentation of the search display, will lead to high saccadic latencies. As a result, manipulation of fixation point offset time is expected to result in a broad range of response latencies and allows us to examine the effect of stimulus-driven and goal-directed control on a variety of response latencies. Observers were told to initiate saccades only after the offset of the central fixation point.

Observers were presented with an array containing one target, multiple non-targets, and one distractor. All elements consisted of line segments rotated along the vertical axis. The task of observers was to make a speeded eye movement to the target as soon as the fixation point set off. In order to investigate the relative

contribution of stimulus-driven and goal-directed control, distractor saliency and target-distractor similarity were independently manipulated; the irrelevant distractor presented was either a salient item[1] in the display or was not, and either looked similar to the target or did not. If differences in search performance are found between those conditions where distractor saliency is high and those where distractor saliency is low, one may conclude that stimulus-driven control processes contribute to visual search performance. In contrast, if differences are found between those conditions where distractor similarity is high and those conditions where distractor similarity is low, one may conclude goal-driven processes to affect search performance[2].

Based on the proposed manipulations we can make a series of predictions. Note that whereas both a bottom-up and a top-down model of attention acknowledge that selection may occur in either a stimulus-driven or a goal-driven manner, the models of attention (i.e. bottom-up *vs*. top-down) disagree to what extent selection is dominated by either stimulus- or goal-driven processes and the direction of the presumed contingency. According to a bottom-up model of saccadic selection, goal-driven selection occurs after, and is contingent on stimulus-driven selection. According to a top-down model of selection, stimulus-driven selection may take place, but only after and contingent upon goal-directed selection.

More specifically, according to a bottom-up model, visual selection is assumed to be initially determined by the stimulus properties in the visual field. As a result, stimulus properties like salience should always affect eye movement behavior, irrespective of saccadic latency. In addition, the effect of any variable affecting goal-driven processes should depend on the efficiency of stimulus-driven processes. According to a top-down model, visual selection is initially determined by the goals of the observer. As a consequence, it is predicted that target-distractor similarity affects eye movement behavior across all saccadic latencies. In addition, the relative salience of the target and distractor might also affect visual selection behavior. However, the extent of the effect is assumed to depend on the target–distractor similarity. If the distractor is similar to the target, the effect of distractor salience is assumed to be larger than if the distractor is dissimilar to the target.

According to models of selection that argue both stimulus-driven and goal-driven influences summate in a general activation map to determine selection (Treisman and Sato, 1990; Wolfe, 1994; Wolfe *et al*., 1989) it is predicted that both stimulus-salience as well as target–distractor similarity will affect target selection irrespective of the moment in time selection occurs.

According to the independent timing account of visual selection, differential results are to be expected between short-latency and long-latency eye movements. It is expected that short-latency saccades will only be influenced by stimulus-saliency. In contrast, in case of long-latency saccades only an effect of target–distractor similarity is expected. Further, no contingency is to be expected between the effects of stimulus-saliency and target–distractor similarity.

METHOD

Participants

14 students of the Vrije Universiteit Amsterdam participated as paid volunteers in one 150-minute session. Participants ranged in age from 19 to 34 and all reported having normal or corrected-to-normal vision. Two people were omitted from the analysis due to poor accuracy (total of >30% error due to poor fixation) resulting in a total of 12 participants.

Apparatus

A Pentium II Dell computer with a 21″ SVGA color monitor (Philips Brilliance 201 P) controlled the timing of the events and generated stimuli. Eye movements were recorded by means of an Eyelink tracker (SR Research Ltd.) with a 250 Hz temporal resolution and a 0.2° spatial resolution. The system uses an infrared video-based tracking technology to compute the pupil centre and pupil size of both eyes. An infrared head motion tracking system was also used. Display resolution was 1024 × 768 pixels. All subjects were tested in a sound-attenuated, dimly lit room with their heads resting on a chinrest. The monitor was located at eye level 75 cm from the chinrest.

Stimuli

Participants performed a visual search task in which they were required to make a speeded saccade to the target. This eye movement was to be initiated only after the offset of a central fixation point. Latency of the fixation point offset was variable, occurring either concurrently with the presentation of the search display (i.e. 0 ms), or 50, 100, 200 or 400 ms following this event.

The target was a line with an orientation of 0° of arc relative to the vertical, and was presented in every trial. Displays consisted of 1 target, a series of non-targets (oriented 45° or −45° of arc relative to the vertical) and 1 distractor (oriented −67.5° or 22.5° of arc relative to the vertical) (see Fig. 1). There were two possible distractor identities (22.5° or −67.5°) and two possible non-target identities (−45° or 45°) resulting in four different combinations of distractor saliency[3] and target–distractor similarity. The absolute difference in orientation between the target and the non-targets was always 45°. The absolute difference in orientation between the two types of distractors and the non-targets was either 22.5° or 67.5°. The distractor was considered a salient item in the display when the absolute difference in orientation between the distractor and its surrounding non-targets was 67.5° (see Fig. 1a and d). In trials in which the distractor had an absolute difference in orientation less than this amount, namely those in which the difference was 22.5°, the distractor was not considered salient (see Fig. 1b and c). In contrast, target distractor similarity was considered high when the distractor was oriented at 22.5°

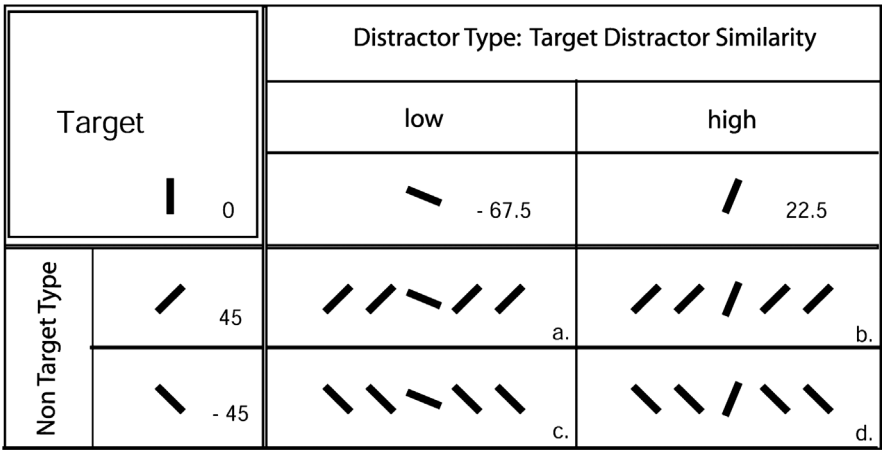

Figure 1. An overview of the stimuli. The target presented is always a vertical line element. Distractors presented were rotated either 67.5° to the left (similarity low) or 22.5° to the right (similarity high). Non-targets are rotated either 45° to the left or 45° to the right. Depending on the surrounding non-targets, distractors appear as salient (case a. and case d.) or not (case b. and case c.).

(see Fig. 1b and d), and target–distractor similarity low when the distractor was oriented at −67.5° (see Fig. 1a and c).

Elements were arranged in a 9×13 rectangular matrix with a raster width of 13.2° and a height of 15.9°. Targets and distractors could appear at six different locations. These six potential locations were placed on an imaginary circle in such a way that, embedded in the matrix of non-targets, targets and distractors were always presented at equal eccentricity from fixation (4.3° of visual angle). When a target and a distractor were presented the angular separation on the imaginary circle between the two elements, measured from the fixation point, was always 120°. Elements had height of 0.76° of visual angle and approximate width of 0.31° visual angle. Elements were white (CIE x, y, coordinates of 0.288/0.316; 93.14 cd/m^2) and were presented on a black background (see Fig. 2).

Design and procedure

A within-subjects design was used. Target-distractor similarity (low and high), distractor saliency (low and high) and fixation point offset interval (5) were varied within subjects. All conditions were varied within blocks of trials. Each participant performed 48 practice trials and 960 experimental trials.

To start a trial participants pressed the spacebar. A fixation point was presented for 1000 ms, followed by the presentation of the stimulus array. The fixation point disappeared at a variable latency (i.e. 0, 50, 100, 200, or 400 ms) following presentation of the search display. After fixation point offset, the stimulus array was presented for 1500 ms. Feedback concerning saccade latency was provided every 30 trials. Participants took a break every 240 trials. Participants were instructed

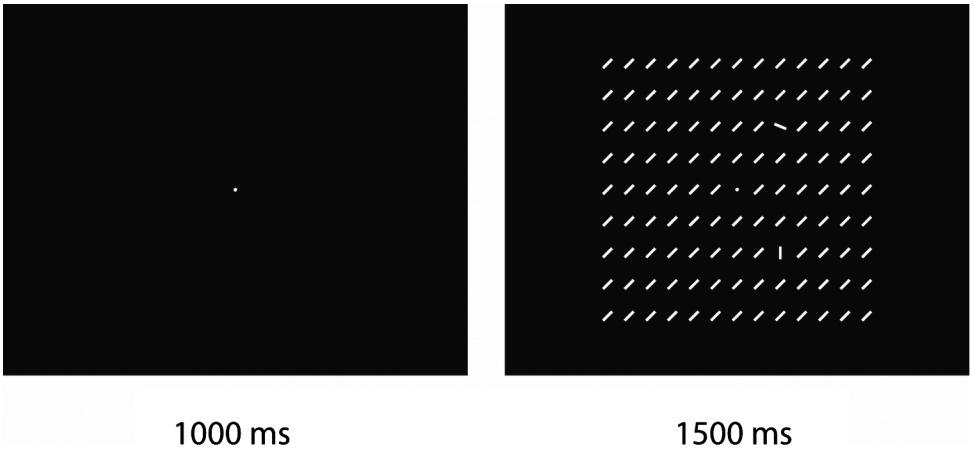

Figure 2. An example of the primary stimulus display. The target of search is the vertical element presented. The homogeneous group of elements (rotated either 45° to the left or 45° to the right) are referred to as non-targets; and the additional and irrelevant orientation singleton is referred to as distractor.

to make a saccade as quickly as possible after the fixation point offset, while maintaining a high level of accuracy. To make sure participants understood the task correctly, both written and oral instructions were given. Prior to the recording, participants viewed a calibration display consisting of nine points in a square array, which were fixated sequentially.

RESULTS

Initial saccade latencies below 80 ms (anticipation errors: 7.2%) and above 600 ms (0.8%) relative to fixation point offset were counted as errors and were excluded from the analyses. In 2.8% of all trials, participant saccades missed the location of either the target or distractor. Misses were defined as saccades with endpoints at least 3° of visual angle away from the target or distractor location. These trials were not analyzed further.

An analysis of variance (ANOVA) was performed on the individual saccade latencies with fixation point offset interval (5 levels) as factor. A main effect of fixation point offset interval was found, $F(4, 44) = 246.67$, $p < 0.01$, indicating that saccade latencies significantly increased with fixation point offset interval. Relative to the presentation of the search display, the fastest saccadic latencies were obtained when the fixation point offset concurrently with the presentation of the search display (mean 304 ms) and the slowest saccadic latencies were obtained when the fixation point offset 400 ms after presentation of the search display (mean 594 ms).

In order to look at the absolute fastest and slowest latencies, saccade latencies were collapsed across fixation point offset condition. For each condition (target–

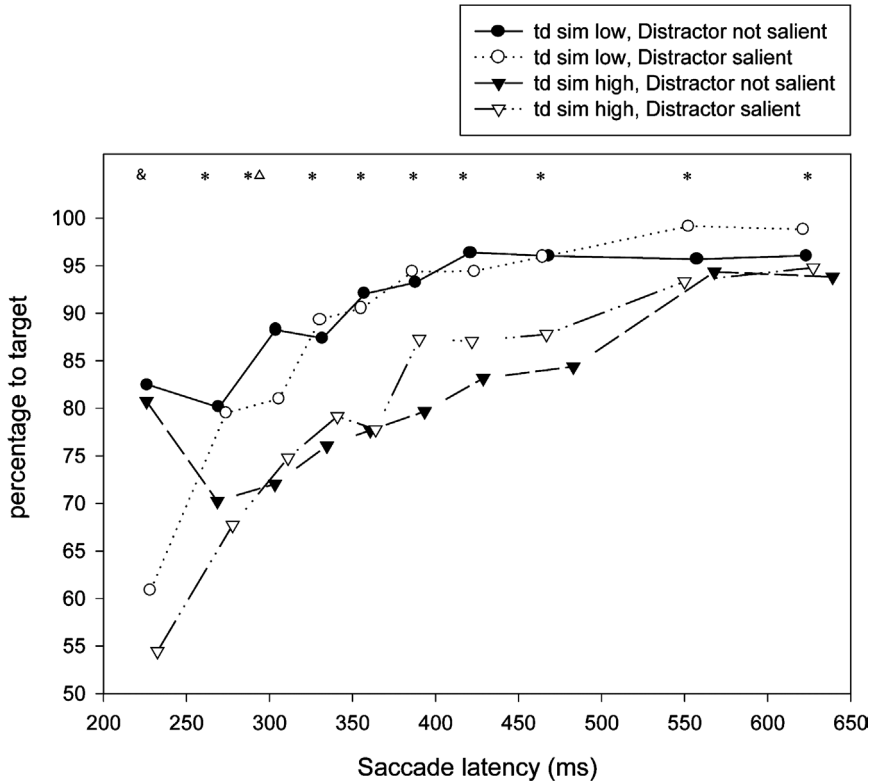

Figure 3. The percentage of eye movements directed correctly toward the target as a function of time. Saccade latencies were collapsed across fixation point offset conditions and divided into deciles (10). For each decile a separate ANOVA was performed on proportion correct eye movements with target-distractor similarity (low and high) and distractor saliency (low and high) as factors. Symbol '$*$' denotes a significant main effect of target-distractor similarity; symbol '&' denotes a significant main effect of distractor saliency, and symbol 'Δ' represents a significant interaction between target-distractor similarity and distractor saliency ($p < 0.05$).

distractor similarity (low and high), distractor saliency (low and high)), and for each participant an individual distribution of the initial saccade latencies was calculated irrespective of the saccade destination. Distributions were divided into deciles (10) based on saccade latency and the proportion of correct eye movements (i.e. eye movements towards the target) was calculated for each decile. For each decile, the average saccade latency was calculated (see Fig. 3). An ANOVA was conducted on the proportion of correct eye movements with target–distractor similarity (low and high), distractor saliency (low and high) and decile (10) as factors. A main effect of target–distractor similarity was found, $F(1, 11) = 111.49$, $p < 0.01$, as well as a main effect of decile, $F(9, 99) = 31.59$, $p < 0.01$. No main effect of distractor saliency was found, $F(1, 11) = 2.01$, $p > 0.1$. No interaction was found between target–distractor similarity and distractor saliency, $F(1, 11) = 1.36$, $p > 0.1$. An interaction was found between target–distractor similarity and

decile, $F(9, 99) = 3.09$, $p < 0.01$, and between distractor saliency and decile $F(9, 99) = 7.67$, $p < 0.01$. The effect of target–distractor similarity changed significantly as a function of saccadic latency, as did the effect of distractor saliency. No interaction was found between target–distractor similarity, distractor saliency and decile, $F(9, 99) = 1.59$, $p > 0.1$.

An ANOVA was performed on the saccadic latencies with target–distractor similarity (low and high), distractor saliency (low and high) and decile (10) as factors. A main effect of target–distractor similarity was found, $F(1, 11) = 11.05$, $p < 0.01$, as well as a main effect of decile, $F(9, 99) = 308.25$, $p < 0.01$. Overall saccadic latencies were slightly slower in cases where the distractor presented did not look similar to the target (mean 394 ms) than when the distractor presented did look similar (mean 399 ms). No main effect of distractor saliency was found, $F(1, 11) = 1.17$, $p > 0.1$. No interaction was found between target–distractor similarity and distractor saliency, $F(1, 11) < 1$, nor was interaction found between target–distractor similarity and decile, $F(9, 99) = 1.21$, $p > 0.05$. An interaction was found between distractor saliency and decile, $F(9, 99) = 5.80$, $p < 0.01$, as well as between target–distractor similarity, distractor saliency and decile, $F(9, 99) = 4.63$, $p < 0.01$.

Separate ANOVAs were performed on each decile on the proportion of correct eye movements to the target. Factors included were target–distractor similarity (low and high) and distractor saliency (low and high). In the first decile (i.e. the fastest eye movements), a main effect of distractor saliency was found, $F(1, 11) = 21.46$, $p < 0.01$. No main effect of target–distractor similarity was found, $F(1, 11) = 1.69$, $p > 0.1$, and no interaction was found between target–distractor similarity and distractor saliency, $F(1, 11) < 1$. In the second decile, a main effect of target–distractor similarity was found, $F(1, 11) = 13.72$, $p < 0.01$. No effect of saliency was found, $F(1, 11) < 1$, nor was an interaction found between target–distractor similarity and distractor saliency, $F(1, 11) < 1$. Except for an interaction between distractor saliency and target–distractor similarity in the third decile, $F(1, 11) = 6.06$, $p < 0.05$, deciles three to ten only yielded significant main effects for target–distractor similarity (see Fig. 3).

DISCUSSION

The results showed that stimulus-saliency and target–distractor similarity affect saccadic target selection differently depending on the response latency. An effect of distractor saliency was found for the shortest latency movements (i.e. first decile) only. In contrast, target–distractor similarity effects were absent for the short-latency eye movements (i.e. first decile) but present in all cases of long-latency eye movements (i.e. second to tenth decile).

The purpose of the present study was to investigate the relative contribution of stimulus-driven and goal-driven control in saccadic visual selection as a function

of time. The results are in accordance with the idea that stimulus-driven and goal-driven selection operate in different time windows (e.g. Cheal and Chastain, 2002; Ludwig and Gilchrist, 2002; Müller and Rabbitt, 1989; van Zoest *et al*., 2004). Initially, saccadic selection appears to be controlled by the stimulus salience. Later in time selection appears to be much more goal-driven, as observed by the effect of target–distractor similarity on the slower eye movements.

The results are also in line with the idea that stimulus-driven and goal-driven selection do not only differ in latency but in time course as well (e.g. Müller and Rabbitt, 1989; Nakayama and Mackeben, 1989; Trappenberg *et al.*, 2001). For example, Müller and Rabbitt (1989) have demonstrated that the effects of stimulus-driven control not only are shorter in time, but also come about faster than the effects of goal-driven control. In the present study, an effect of distractor saliency was observed only for the absolute shortest-latency eye movements and was absent for the long-latency eye movements. The effect of target–distractor similarity was observed later in time than the effect of distractor saliency yet was found across the majority of saccadic responses. Thus, while the effect of distractor saliency was fast and transient, the effect of target–distractor similarity was slow and sustained (see also Nakayama and Mackeben, 1989).

The findings of the present study are difficult to reconcile with views of visual selection that have argued selection is predominantly stimulus-driven, or predominantly goal-driven. According to a bottom-up model of saccadic target selection, selection is initially controlled by saliency (Engel, 1977; Godijn and Theeuwes, 2002; Kramer *et al*., 1999; Theeuwes and Godijn, 2001; Theeuwes *et al*., 1999). Furthermore, an effect of target–distractor similarity may exist but is assumed to depend on whether or not elements were selected on the basis of saliency in the first place. While our results are in line with an account of selection that assumes initial dominance of stimulus-driven control, our results are not in line with the idea of a contingency between stimulus-driven and goal-driven control. If goal-driven control had been contingent upon stimulus-driven control, one would have expected to find an interaction between target–distractor similarity and distractor saliency. In other words, conditioned on initial stimulus-driven selection, an effect of target–distractor similarity was expected. In this case, one would have expected to find a larger effect of target–distractor similarity in cases where the distractor was salient. Our results showed that target–distractor similarity affected search completely independently of distractor saliency. Furthermore, saliency effects should have been consistently present across the entire range of saccade latencies. In the present study, the effect of saliency was only observed for the fastest eye movements and was completely absent for the slower eye movements. Thus, the ability to make a goal-directed eye movement was not conditioned on early stimulus-driven control. This latter finding strongly argues against the idea that visual selection is contingent upon stimulus-driven control.

According to a goal-directed view of saccadic selection, selection is predominantly controlled by the goals and intentions of the observer (e.g. Findlay, 1997).

In line with a goal-directed account of selection, the results showed that for the majority of saccadic latencies, target–distractor similarity influenced selection performance. However, performance was initially controlled by stimulus-saliency. According to a strict goal-directed account of saccadic selection, stimulus-saliency need not influence performance. The results of the present study are not in line with the idea that saccadic selection is initially controlled by the goals and intentions of the observers. While goal-driven selection was possible after a minimal time period had elapsed, initially goal-directed saccadic selection was not possible.

Further, the results of the present study are not line with a model of visual selection that argues that the effects of stimulus-driven and goal-driven control summate to jointly influence the allocation of attention (e.g. Wolfe, 1994; Wolfe *et al*., 1989). If this had been the case, we should have found both an effect of stimulus-salience as well as an effect of target–distractor similarity across all saccadic latencies.

The result of the present study suggests that the contributions of stimulus-driven and goal-driven control independently vary in time. The results are in support of the independent timing account of visual selection (van Zoest and Donk, 2005; van Zoest *et al*., 2004). The results of the present study are in line with other models of visual selection that also assume that stimulus-driven and goal-directed processes independently affect oculomotor behavior (e.g. Theeuwes *et al.*, 1998). Looking at the existing literature regarding these models, it is possible to distinguish between two different types of models. One type assumes complete independence between stimulus-driven and goal-directed control (Irwin *et al.*, 2000; Theeuwes *et al.*, 1998, 1999) whereas another type assumes independence up to a certain processing level where both types of control converge in a common saccade map (Findlay and Walker, 1999; Godijn and Theeuwes, 2002; Kopecz, 1995; Trappenberg *et al.*, 2001).

The idea of complete independence between stimulus-driven and goal-directed control in oculomotor behavior was initially motivated by studies showing that the planning and the execution of a goal-directed eye movement was disrupted by the appearance of an irrelevant abrupt onset. In a study carried out by Theeuwes *et al*. (1999; but see also Irwin *et al*., 2000; Theeuwes *et al*., 1998), participants were required to make an eye movement to a color singleton and respond to the identity of a small letter located inside the color singleton. At different SOAs after the presentation of the color singleton, a task-irrelevant abrupt onset was presented somewhere in the visual field. The results demonstrated that in many instances the appearance of the abrupt onset caused the eyes to move to the onset instead of to the color singleton. Theeuwes *et al*. (1999) proposed that in preparing a voluntary eye movement, observers allocate their attention to the location of the saccade target in a goal-directed manner. When simultaneously, a highly salient but irrelevant other object appears at another location in the visual field, stimulus-driven attention is drawn to that object. Theeuwes *et al.* argue that two eye movements can be independently programmed in parallel. Like in a simple horse race, Theeuwes *et al.* assume that the eye movement program that is ready first will go in a winner-

take-all fashion resulting in either a stimulus-driven or a goal-directed generated eye movement. The results of the present study are in line with models that assume eye movements are either stimulus-driven or goal-directed.

Nevertheless, recently, the idea of independent programming has been challenged (Godijn and Theeuwes, 2002). Godijn and Theeuwes suggest that stimulus-driven and goal-driven signals are integrated by dynamic competition. In their study, using the same paradigm as Theeuwes *et al.* (1999), they demonstrated that the presence of an irrelevant onset distractor affects correct saccades toward the target. More specifically, saccade latencies towards the target were longer when the target and onset distractor were presented relatively far apart compared to when they were presented relatively close together. Furthermore, the trajectories of the saccades towards the target were curved in the contralateral direction relative to the onset distractor. On the basis of their results, they concluded that stimulus-driven and goal-directed saccades are not independently programmed but derive from activation in a common retinotopic saccade map. According to their competitive integration model of saccade programming, stimulus-driven and goal-directed activation are integrated at a common site. Activity at a specific location in the saccade map may spread to neighboring locations but inhibit distant locations. In addition, it is assumed that stimulus-driven activation evoked by a salient element may be top-down inhibited to prevent the eyes to be captured (Tipper *et al.*, 2000, 2001). The execution of a saccade is triggered when the activation at a specific location in the saccade map reaches threshold (see for similar accounts, Kopecz, 1995; Trappenberg *et al.*, 2001). In line with neurophysiological evidence, Godijn and Theeuwes (2002) assume that the superior colliculi play a crucial role in the programming of saccades. Accordingly, they suggested that the intermediate layers of the superior colliculi integrate stimulus-driven and goal-directed saccade-related activity.

One way to fit the assumed independence of stimulus-driven and goal-directed processing found in the present study with the proposed competitive integration of these two processes in one saccade map (i.e. Godijn and Theeuwes, 2002; Koch and Ullman, 1985), is to assume that both processes occur at different stages in time. Indeed, the ideas of the present study are well in line with work by Trappenberg *et al.* (2001). They argue that stimulus-driven input may reach the saccade map without extensive processing whereas goal-directed input requires interpretation by higher processing centres. As a consequence, stimulus-driven generated saccades are assumed to occur earlier in time than goal-directed generated saccades. Moreover, Trappenberg *et al.* proposed that stimulus-driven and goal-directed inputs also differ in their time-course. They assume that after an initial rise, stimulus-driven generated activation may decline shortly after presentation due to lateral inhibition within the saccade map. This would imply that at the time that goal-directed generated activation arrives at the saccade map, stimulus-driven activation has already decayed. As a consequence, eye movements are either

stimulus-driven or goal-directed as a product of response time. This idea is in strong accordance with the data presented in this paper.

Furthermore, neurophysiological evidence is in line with the proposed timing account of visual selection. Earlier rather than later visual areas along the visual pathways are likely to be responsible for the fast and transient stimulus-driven control. For example, Li (2002) pointed out that it is possible that the primary visual cortex (V1) may serve the purpose of a stimulus-driven salience map. Several studies suggest that even though cells in V1 are tuned to specific features (Hubel and Wiesel, 1968), their output in terms of salience might be equivalent (Li, 2002). In other words, V1 may signal the presence of salience irrespective of the specific feature(s) that signal it (Itti and Koch, 2000; Li, 2002; Nothdurft, 2002). Moreover, micro-stimulation of the striate cortex increases the probability of saccades and decreases the latency of saccades made to the target in the receptive field of the stimulated neurons (Tehovnik *et al.*, 2003). Supporting this idea is the fact that V1 sends outputs directly to the SC, the SC being the location that ultimately controls saccadic selection (Schall, 1995).

In line with the idea that goal-driven control dominates cases of late selection, neurophysiological evidence suggests that goal-driven, knowledge-driven selection takes time to take effect. For example, effects of target stimulus knowledge are not manifested in the neural responses in inferior temporal cortex (IT) until 150–200 ms after stimulus onset (Chelazzi *et al.*, 1998). Chelazzi *et al*. showed that that initially, most cells responded the same, regardless whether a target or distractor was presented in the visual field. Only after a minimal amount of time, cell activity became significantly larger when a target was in the receptive field than when a distractor was in the receptive field. Similar patterns of results have been reported in the SC (McPeek and Keller, 2002) and in the frontal eye fields (Schall and Hanes, 1993; Schall *et al.*, 1995; Thompson *et al.*, 1996). Suggestions like these can be accommodated by a timing account of visual selection.

In sum, the results of the present study suggest that stimulus-driven and goal-directed control influence saccadic search performance independently. Furthermore, whereas stimulus-driven control dominated early saccadic selection, goal-directed control dominated late saccadic selection.

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NOTES

1. Stimulus-salience is defined by regions that are different from their surround on one or more feature dimensions, such as color, intensity and contrast (Itti and Koch, 2000, 2001); in the present study, saliency was qualified only by a difference in orientation between an element and its surrounding elements.

2. Note that other variables than prior knowledge of the target identity may affect goal-driven control of selection. Goal-driven selection may also encompass factors such as gist and layout, short-term visual memory for previously attended information in the current scene, and stored long-term visual, spatial and semantic information about other similar scenes (see Henderson, 2003).
3. It should be noted that the size of an orientation difference between an element and its background is directly correlated with the saliency of this element, i.e., the larger the difference in orientation, the faster the detection time (e.g. Wolfe and Friedman-Hill, 1992).

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